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Rosatom State Atomic Energy Coproration & National Research Nuclear University “MEPhI”

Course: Fundamentals of Modern Russian designed NPP with VVER 1200 power reactor

Module 2: Engineering fundamentals of nuclear power generation. Basics of VVER technology

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RUSATOMSERVICE

Fundamentals of Modern Russian designed NPP with VVER 1200 power reactor

2. Engineering fundamentals of nuclear power generation. Basics of VVER technology

The terminal training objectives of the second part of the course are as follows: first, the physical aspects of nuclear fuel burnup are discussed—this is one of the main characteristics of reactor performance from the viewpoint of economic efficiency and many other factors. Second, main specific features of VVER technology are described in comparison with the western type reactor (PWR).

The corresponding enabling training objectives are:

- to describe the mechanism of nuclear fuel burnup;
- to identify the contribution of uranium and plutonium to energy release in a power reactor;
- to describe the reactivity coefficients and their relation to safety;
- to list distinguishing features of VVER technology vs PWR technology.

The following topics are covered in this part of the course:

1. structural materials of nuclear power reactors;
2. the concept of fuel burnup;
3. plutonium accumulation in nuclear power reactor;
4. basics of safe operation of nuclear power reactors: relativity effects;
5. comparison of specific characteristics of VVER technology versus pressurized water reactors (PWR) technology;
6. advanced nuclear fuel types for nuclear power reactors in Russia.

2.1. Structural materials of nuclear power reactors

There is a great variety of nuclear power reactors (NPR), but it is not difficult to classify them, because, as mentioned in the previous section of the course, the main components of reactors are moderators and fuel. So, the classification of NPRs is based on the combination of the quality of moderator and quality of the fuel. These combinations are presented in Table 2.1.1.

Characteristics of moderator	Characteristics of fuel
Low neutron capture (heavy water D_2O)	Natural uranium U-235: content 0.7%
Medium neutron capture (graphite)	Enriched uranium U-235: content 2%
High neutron capture (light water H_2O)	Enriched uranium U-235: content 3-5%

Table 2.1.1. *Combinations of fuel and moderator.*

As mentioned in section 1.5, heavy water (deuterium oxide) has the lowest neutron capture cross-section. Since neutron capture in heavy water is not so intensive, natural uranium could be used as fuel. The combination of heavy water and natural uranium with uranium-235 content of about 0.7% is implemented in the Canadian-type reactor ***CANDU*** (Canada Deuterium Uranium).

The second combination of moderator and fuel uses graphite, which has medium neutron capture cross-section. Medium cross-section means that the content of uranium-235 has to be increased, or in other words, uranium has to be enriched. For medium neutron capture graphite moderation, the enrichment of uranium is usually expected to reach the level of several percent (about 2%). This combination was implemented in ***RBMK***-type reactors, which are used in Russia.

The most popular type of reactor uses general water as moderator—***PWR*** (pressurized water reactor); ***VVER*** (or WWER: water-cooled water-moderated energy reactor) is among them. High neutron capture of general water requires an increase of the uranium-235 content to about 3-5%.

This is the whole spectrum of possible reactors which are commercially used in the world, depending on the quality of moderator and as a consequence, the quality of fuel in terms of enrichment.

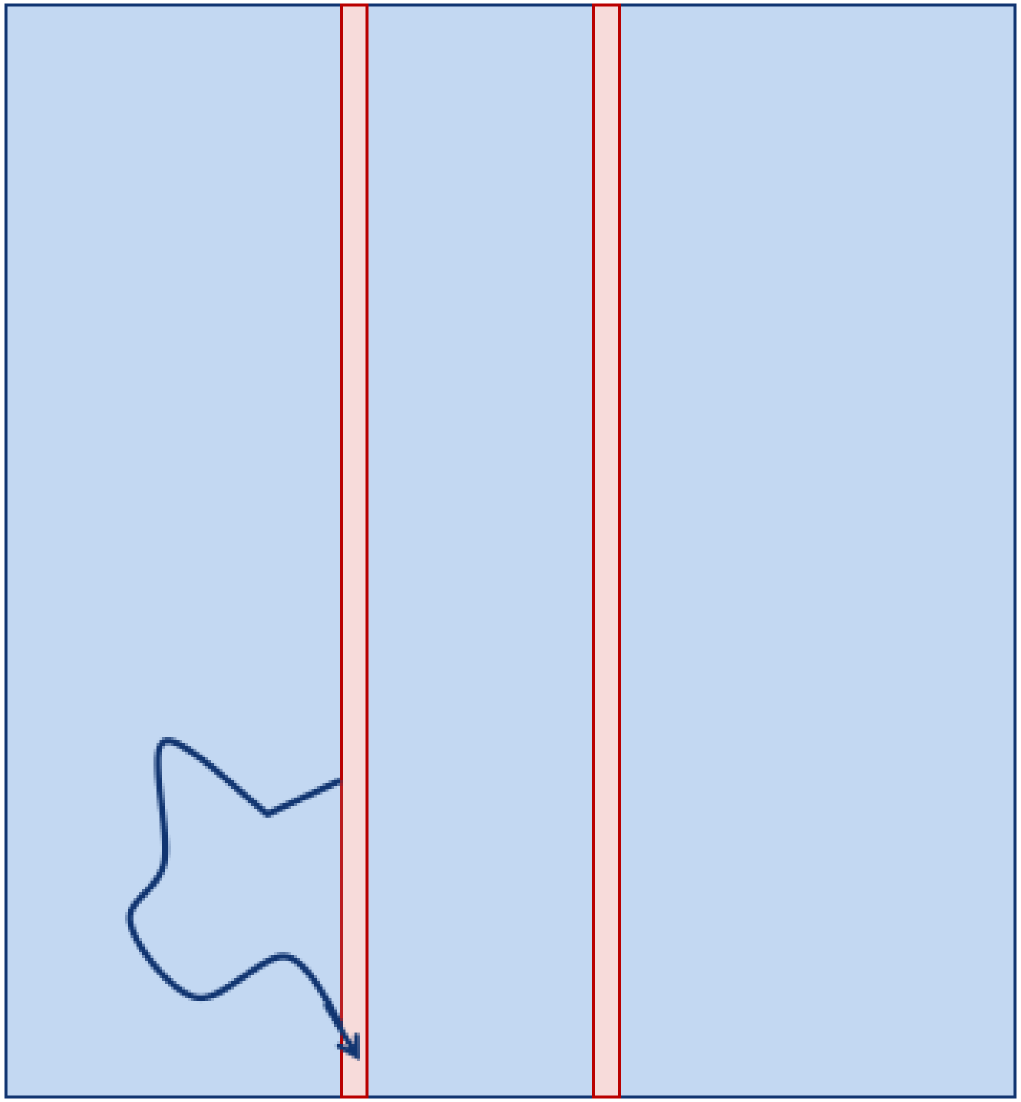

Figure 2.1.1. *Heterogeneous reactor: fuel is separated from moderator.*

On selection of fuel form (radiation induced swelling)

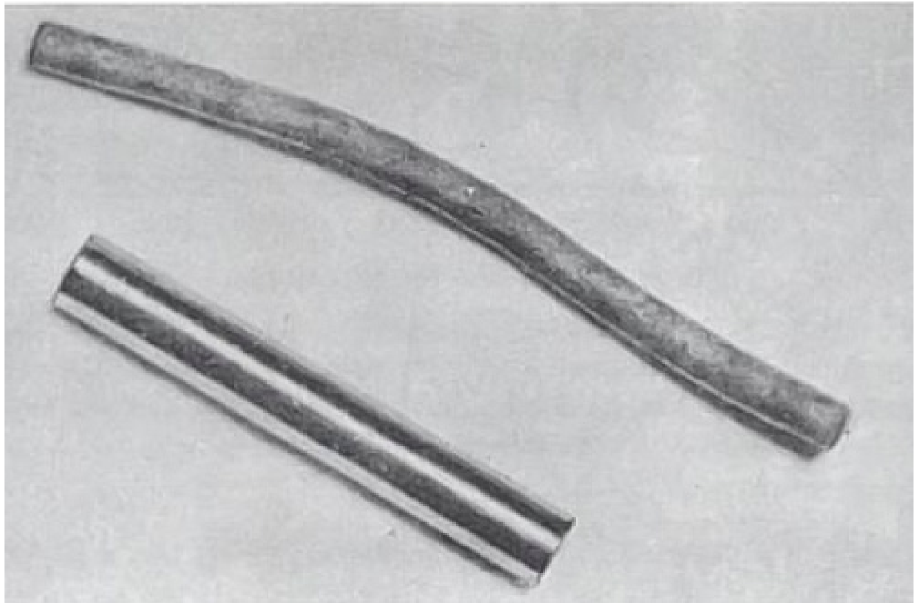

Figure 2.1.2. *Irradiation-induced growth of a uranium rod: upper rod – after irradiation, lower – before. (From A. N. Holden, Physical Metallurgy of Uranium, © 1958, Addison-Wesley, Reading, Massachusetts, Fig.11-1. Reprinted with permission.)*

Figure 2.1.2 illustrates uranium fuel in two conditions. The lower rod has a clean cylindrical shape: this is uranium metal before irradiation. The upper rod is shaped drastically differently from the lower: it is the same fuel rod but after irradiation in the reactor. The form and the volume of the fuel element has changed.

Metal uranium has to be treated very carefully in the reactor. If the volume changes, the whole structure changes. The change of the structure might lead to destruction of the material, in which case there is a possibility for radioactive materials and fission products to escape nuclear reactor and to move into the environment. This is why structural materials of the reactor are very important from the viewpoint of technology. Physics of NPRs is clear and simple, but not many countries, even possessing the knowledge of nuclear physics, can implement the technology. There are only six nuclear technology vendors in the world. So, technology, and the form of structural materials in particular, is of high importance.

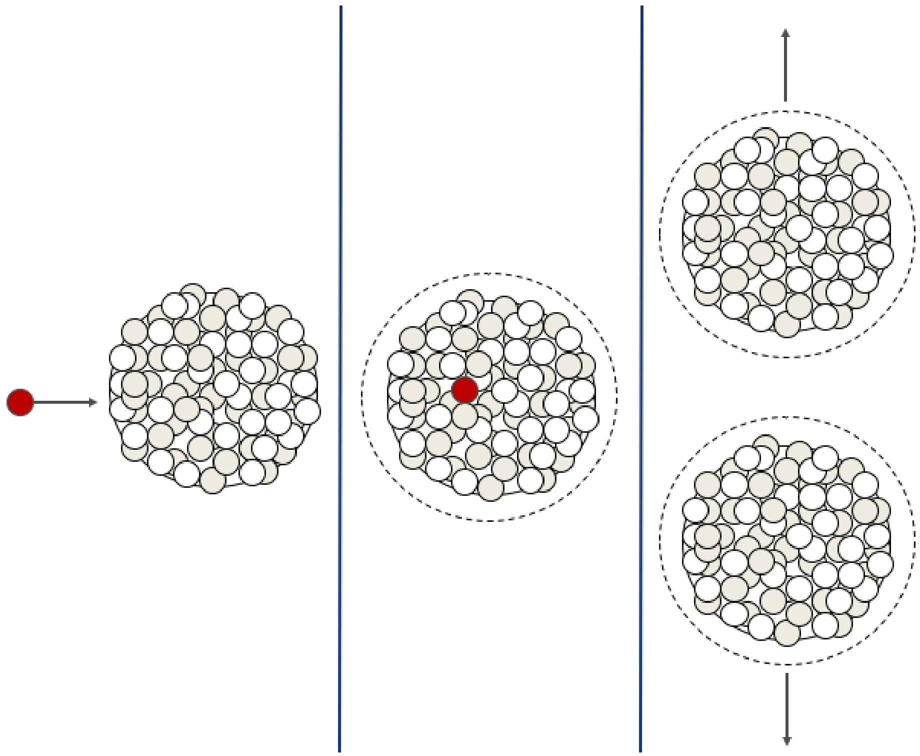

Figure 2.1.3. *A diagram of the fission process.*

Main structural elements of NPRs

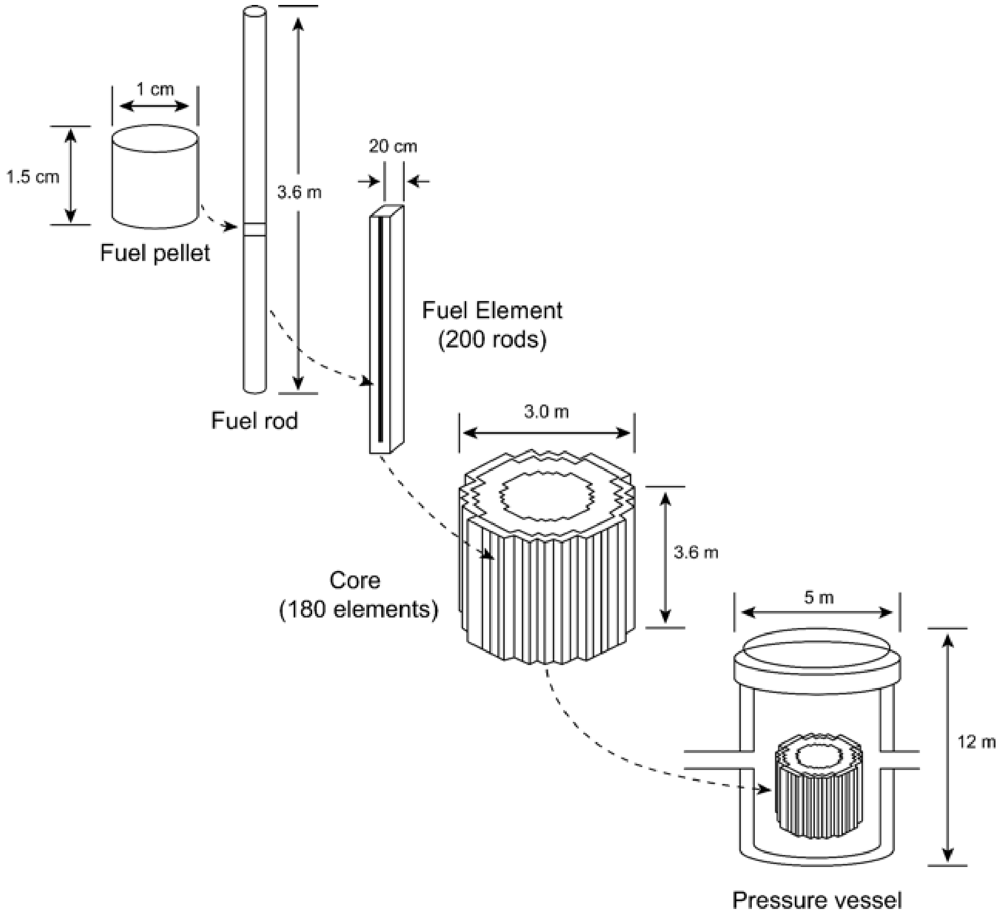

Figure 2.1.4. *Main structural elements of NPR.*

The structure of a reactor is shown in Figure 2.1.4. ***Fuel pellet*** is the heart of energy release. In modern reactors, for example in pressurized water reactors (PWRs) and VVERs, uranium pellets are made not from metallic uranium but from uranium dioxide, which has been experimentally and technologically proven to be a more suitable form of uranium fuel. A fuel pellet is about 1 cm high and 1 cm in diameter. Fuel pellets are put in a so-called ***fuel rod***, fuel rods are combined into a ***fuel assembly*** (fuel element in Figure 2.1.4), fuel assemblies are combined to form a ***reactor core***. The reactor core is then placed into a ***reactor vessel***, which is the vital center of nuclear power plants. Fuel pellet, fuel rod, fuel assembly (element), reactor core, and reactor vessel are the main components of the reactor structure.

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Figure 2.1.5. *Fresh fuel pellets.*

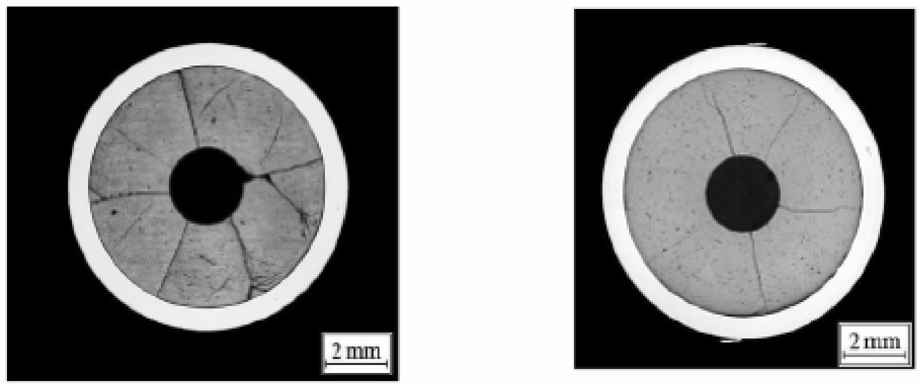

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Figure 2.1.6. *Fuel pellets after irradiation.*

Figures 2.1.5 and 2.1.6 illustrate the effect of irradiation on fuel pellets. During and after irradiation, the structure of the fuel pellet is dramatically changed: both shown pellets have fissures and the one on the left has a hole inside. This structural change should not affect the fuel element coating (cladding). Otherwise, radioactive material might move into reactor moderator, then into reactor coolant, and finally into the environment.

2.2. *Concept of fuel burnup*

Fuel burnup

Fuel burnup is the main process influencing the reactor economic efficiency and waste management technology. The basic diagram of the process is presented in Figure 2.2.1.

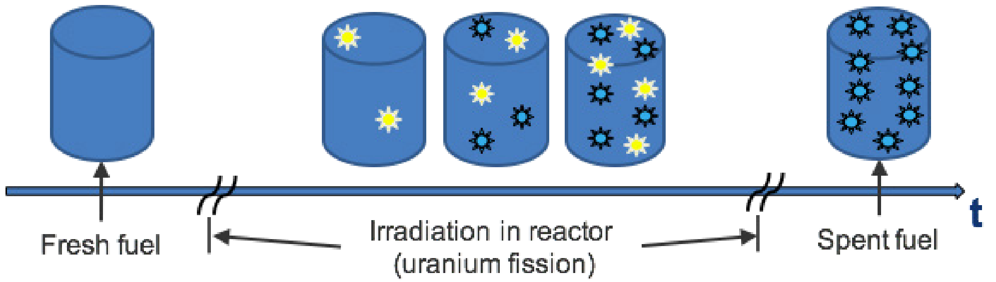
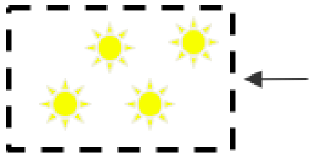


Figure 2.2.1. *The process of fuel burnup.*

At first, there is a fresh fuel pellet before irradiation. The second fuel pellet has two flashes marked in yellow illustrating two fission reactions. The third pellet has different yellow flashes—these are fission reactions propagated in the chain reaction—and several blue flashes in the places where fission reaction has already occurred. Finally, the spent fuel pellet has many blue flashes, which means it has been irradiated in the reactor, and fission reaction occurred inside.

E = 200 MeV/fission

The energy release from the fuel can be easily estimated considering the fact that one fission produces about 200 MeV.



1 Wt ≈ 3.1 × 10¹⁰ fissions/sec

E = P × t, where E denotes energy, p – power, t – time.

$$B = \frac{MWt - days}{kg_{HM}} = \frac{GWt - days}{t_{HM}},$$

where HM denotes heavy metals (fuel).

In continuously irradiated fuel, the energy release might be expressed in megawatts (MWt) times days divided by kilograms of heavy metals, which is exactly ***fuel burnup***—how much energy can be extracted from a unit of fuel material. The higher the fuel burnup, 1) the more energy is produced from the fuel, 2) the more plutonium is produced in the fuel (plutonium production is discussed later), and 3) the more radioactive the spent fuel is. Highly radioactive spent fuel is more difficult to operate with.

Fuel swelling

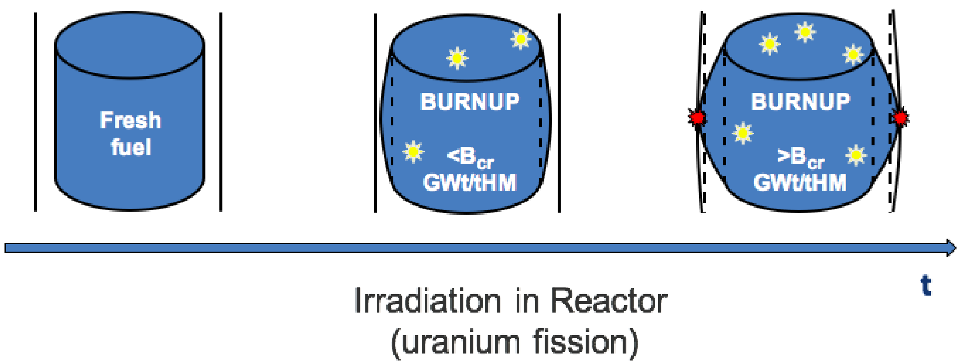


Figure 2.2.2. *Fuel-cladding contact, where B_{cr} denotes the critical level of fuel burnup.*

As discussed in section 2.1, fuel rods can change their shapes during and after irradiation. The same process occurs in fuel pellets, illustrated in Figure 2.2.2. The goal is to prevent the interaction of the swelling fuel pellet with the coating (cladding). Initially, solid fission products have density lower than uranium, which inevitably leads to the process of swelling. During irradiation, gas (Xe – xenon, Kr – krypton) fission products are produced beside solid fission products, which increases pressure inside the fuel. The combination of swelling and gas pressure in the fuel is the main technological parameter that needs to be controlled to prevent radioactivity release in the moderator and into environment. The higher the fuel burnup, the higher the fuel swelling and the higher the probability of fuel-cladding interaction.

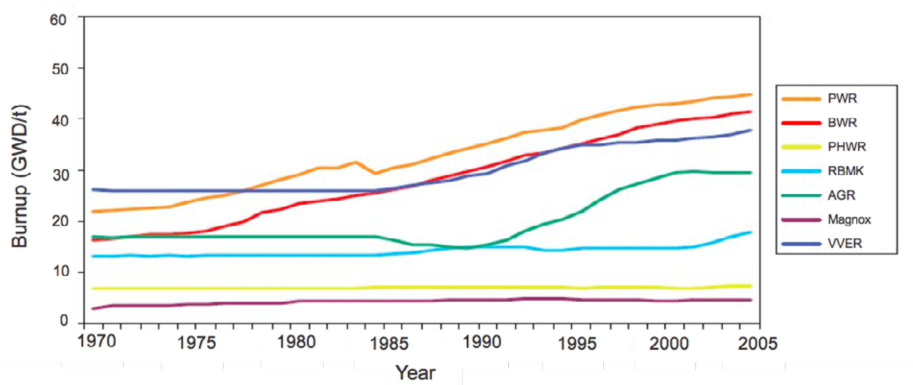


Figure 2.2.3. *Trends in fuel burnup for different types of reactors.*

Fuel burnup is different from reactor to reactor. Figure 2.2.3 is originally taken from Nuclear Technology Review, the document which is annually published in the International Atom

ic Energy Agency (IAEA). The graph illustrates the evolution of fuel burnup characteristics starting from 1970s until 2005. The general trend for pressurized water reactors (PWR), boiling water reactors (BWR), and VVER is to increase fuel burnup. The higher the burnup, the more energy can be extracted and the more cost-effective the energy production is. The general numbers for the burnup are: in PWR the reasonably achieved level of fuel burnup is about 40 gigawatt-day per tonne of heavy metal (GWD/t). For BWR, the level is slightly lower than for PWR. VVER has again a slightly lower level of burnup. The level of burnup in other types of reactors, like CANDU (PHWR) and RBMK, is distinctly lower.

Composition of spent fuel

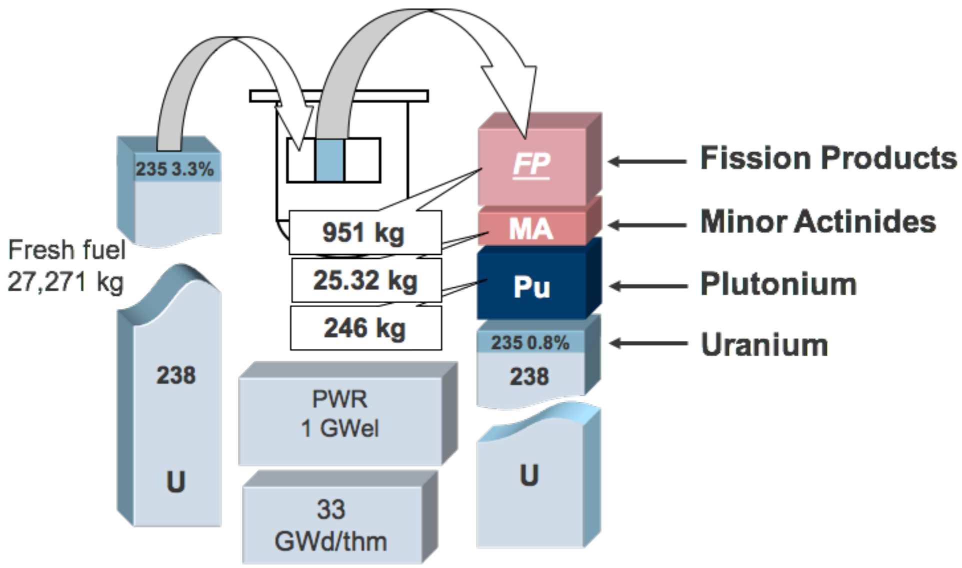


Figure 2.2.4. *Composition of the fresh and the spent fuel.*

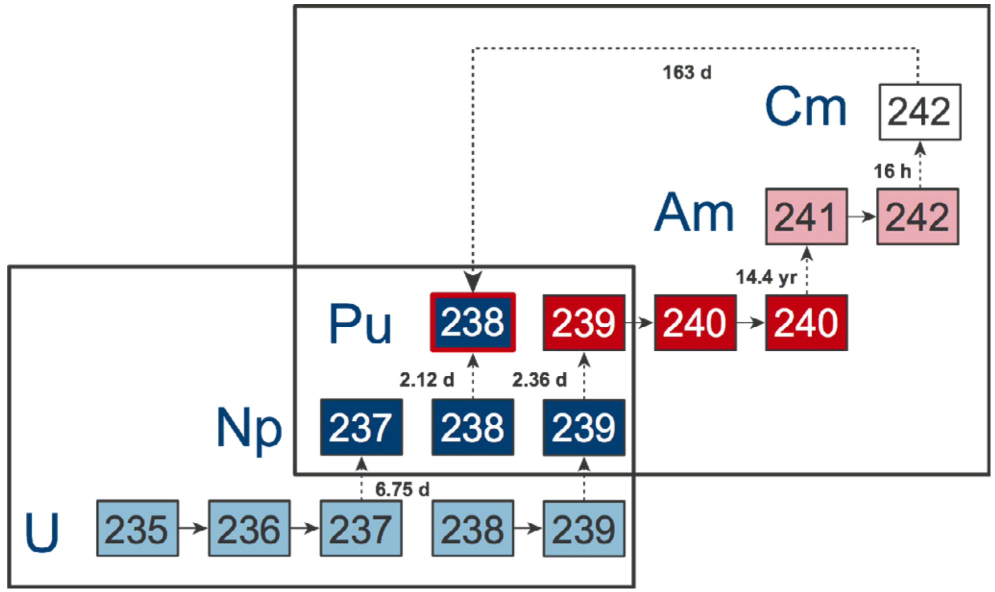
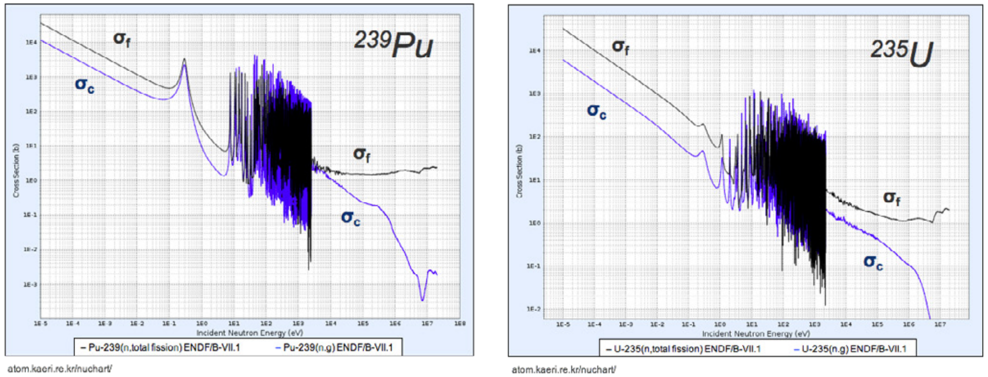


Figure 2.2.5. *Minor actinides production.*

The burnup also influences the composition of the fuel. When fresh fuel is put in the reactor, it consists—in terms of heavy metals—only of uranium, uranium-238 and uranium-235. The uranium-235 fraction is roughly several percent. After irradiation, the portion of uranium-235 in the spent fuel is less than initial, because it is the most fissionable material in the reactor. Due to neutron capture in uranium-238, there is accumulation of heavy nuclides, such as plutonium (Pu), and minor actinides (MA); fission products (FP) are produced as a result. So, in the spent fuel, the main components are: uranium with reduced fraction of uranium-235, accumulated plutonium, minor actinides, and fission products. Figure 2.2.5 presents a scheme of minor actinides production through neutron capture.

2.3. Plutonium accumulation in nuclear reactor

Plutonium



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^{239}Pu	0.0253-eV	Resonance Integral	Fiss. Spec. Average
Fission	747.4 (b)	301.0 (b)	1.802 (b)

^{235}U	0.0253-eV	Resonance Integral	Fiss. Spec. Average
Fission	585.1 (b)	274.4 (b)	1.218 (b)

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Figure 2.3.1. *Cross-sections of plutonium-239 and uranium-235; fissile properties of plutonium-239 are superior compared to uranium-235.*

Apart from being used for weapons manufacturing, proverbial plutonium is also accumulated in reactors. It is worth comparing plutonium-239 with uranium-235. In Figure 2.3.1, two basic characteristics of these nuclides are shown: fission cross-section and capture cross-section. For both plutonium-239 and uranium-235, fission cross-section dominates capture cross-section over the whole energy range. Plutonium-239 is an excellent fissile material. Importantly, the difference between fission cross-section and capture cross-section in high energies for plutonium-239 is preferable to the same characteristic for uranium-235 from the viewpoint of propagation of chain reaction. So, fissile properties of plutonium-239 are superior compared to uranium-235. Accumulated plutonium in the reactor undergoes fission inside the reactor itself.

Plutonium accumulation as a function of burnup

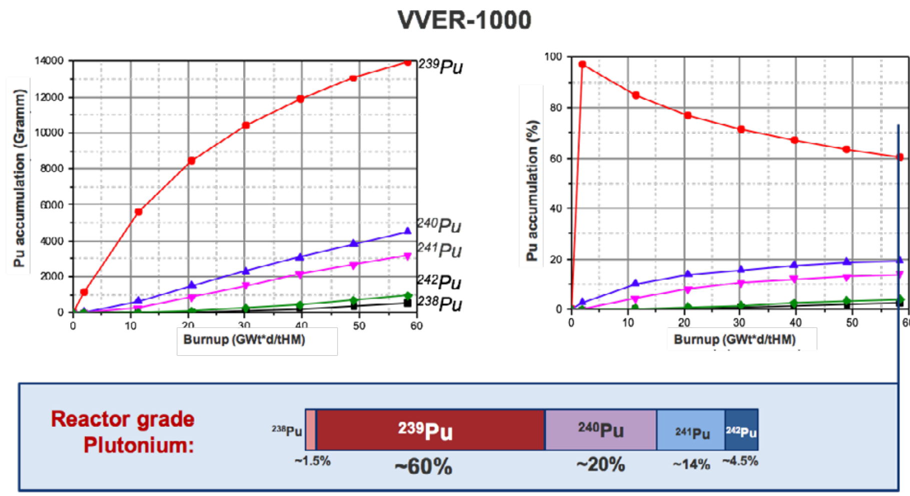

Figure 2.3.2. *Plutonium accumulation as a function of fuel burnup.*

Plutonium is accumulated and fissioned in the reactor. It is interesting to note that composition of plutonium in spent fuel is: plutonium-238 – about 1.5%, plutonium-239 – about 60%, and other plutonium isotopes (Pu-240, Pu-241, Pu-242). Remarkably, only one isotope of plutonium is used in nuclear weapons—plutonium-239. Nuclear reactor, however, produces a composition of isotopes. These isotopes (plutonium-238, plutonium-240) drastically decrease the attractiveness of the produced plutonium for nuclear weapon technology. Which means that civil plutonium accumulated in nuclear reactors is not so dangerous in terms of proliferation of nuclear materials. It can be used, and it is used, for energy release inside the reactor.

2.4. Basics of safe operation of nuclear power reactors: reactivity effects

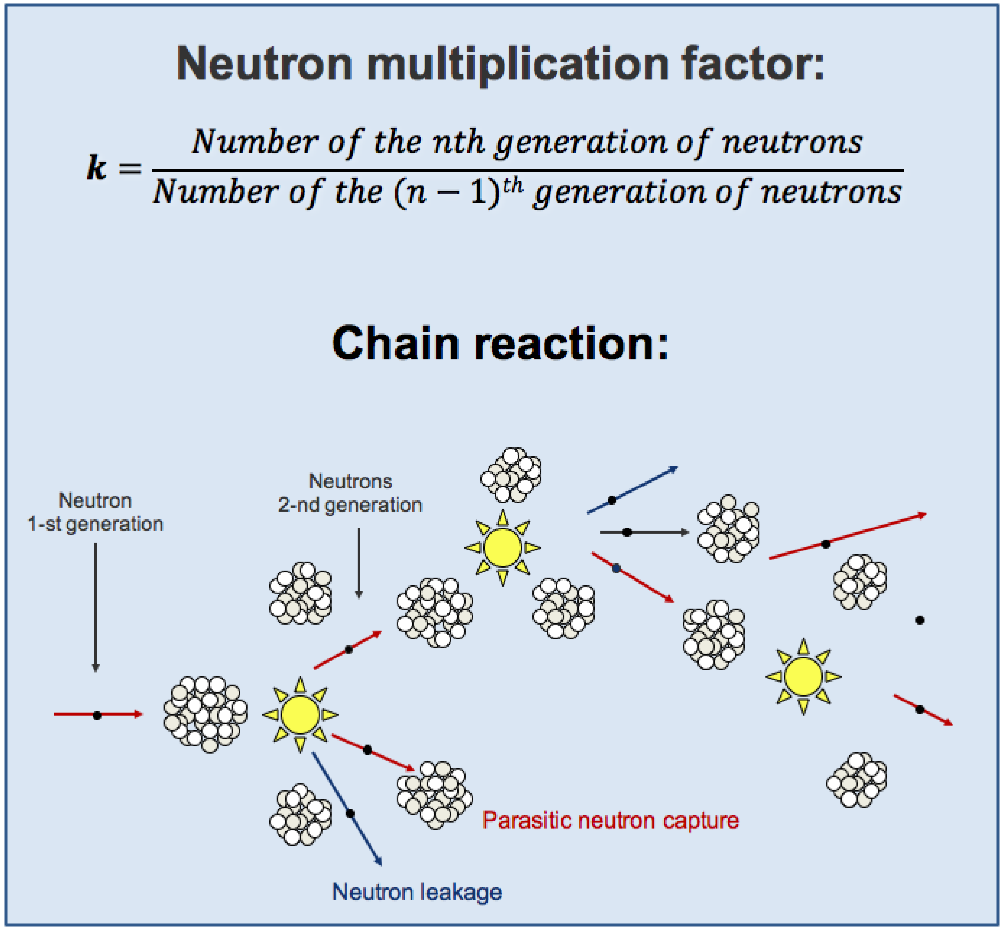

Figure 2.4.1. Neutron multiplication factor and chain reaction.

Next, nuclear properties of the fuel which affect safety are discussed. The main characteristic for the safety assessment of a reactor is the ***neutron multiplication factor*** (NMF), which was covered in section 1.5. If NMF is higher than unity, chain reaction intensifies; special care should be taken to control it. Reactor stability is achieved at the level when NMF is equal to unity. So, the difference between NMF and unity (k – 1)—called ***excess multiplication***—has special meaning.

Fractional excess multiplication is excess multiplication divided by MNF: (k – 1)/k. The same parameter could be called ***reactivity***, which might be more intuitively understandable. Reactivity is a dimensionless quantity that characterizes propagation of fission chain reaction in the reactor core.

$\rho = (k - 1) / k = k / k$

The higher the reactivity, the more intensive the fission reaction is in the reactor. If the reactivity is lower, the reactor could be shut down. All safety parameters are affected by reactivity.

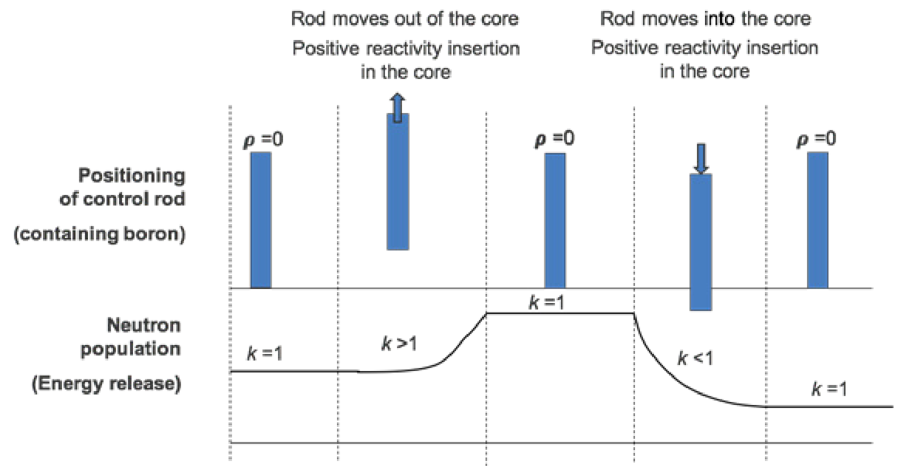

Figure 2.4.2. Modes of reactor operation in terms of reactivity.

If the reactor is in stable operation, NMF is equal to unity, reactivity at this moment is zero. If the level power in the reactor is increased, NMF exceeds unity and reactivity becomes positive. If the reactor is shut down, NMF is reduced to a level less than unity and reactivity is negative. In terms of safety, positive reactivity is dangerous, zero reactivity is optimal, and negative reactivity is an indicator of reactor shutdown.

Doppler coefficient (DC)

Safety of reactors is estimated in terms of reactivity effects, the most important of which are discussed in the following sections. The first reactivity effect is the ***Doppler coefficient*** (DC). DC influences reactivity due to the temperature effect on neutron capture. DC is the change in reactivity per degree change in fuel temperature:

$DC = (\rho(T_2) - \rho(T_1)) / \Delta T$, *where* $T_2 > T_1$ *and T denotes fuel temperature.*

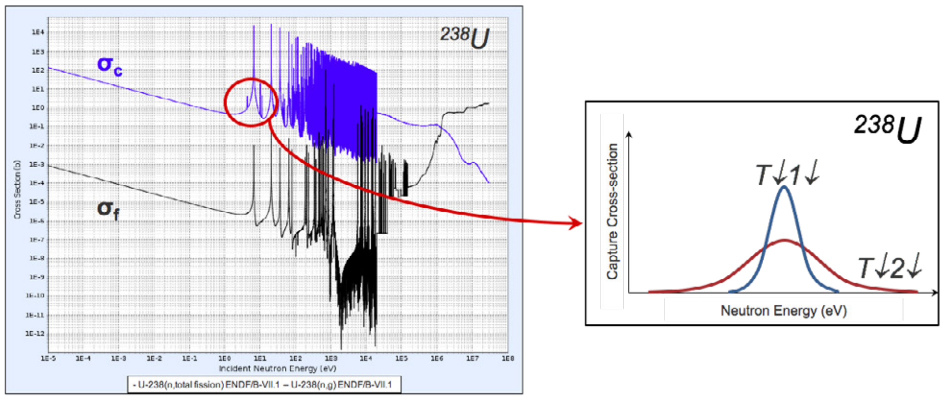

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Figure 2.4.3. *Capture cross-section of uranium-238.*

Figure 2.4.3 illustrates the resonance in capture cross-section of uranium-238. Temperature T1 is sharply peaked. If the temperature is increased, the form is changed, and the area below the curve becomes larger. The larger the area, the more neutrons are to be captured. In other words, the temperature is increased in the fuel, neutron capture in uranium-238 is increased, and the reactivity is decreased. Importantly, DC should be negative in order for the reactor to be operated in safe and stable manner.

To summarize, temperature increases, neutron capture increases, reactivity decreases. If something uncontrolled happens in the reactor, increased temperature presents the most danger. If the temperature increases, there is a probability of the fuel melting and of radioactivity release in the environment. But the reactor works in the opposite manner: if the temperature increases, neutron capture increases, and the reactor shuts down by itself. This phenomenon is called inherent safety: the reactor shuts down by itself due to Doppler effect.

Moderator temperature coefficient (MTC)

Another important characteristic for safety of the reactor is the moderator temperature coefficient (MTC). This effect is again explained in terms of cross-section.

$DC = (\rho(T_2) - \rho(T_1)) / \Delta T$, *where T denotes moderator temperature.*

Moderator temperature coefficient (MTC) is the change in reactivity per degree change in moderator temperature. It should be negative.

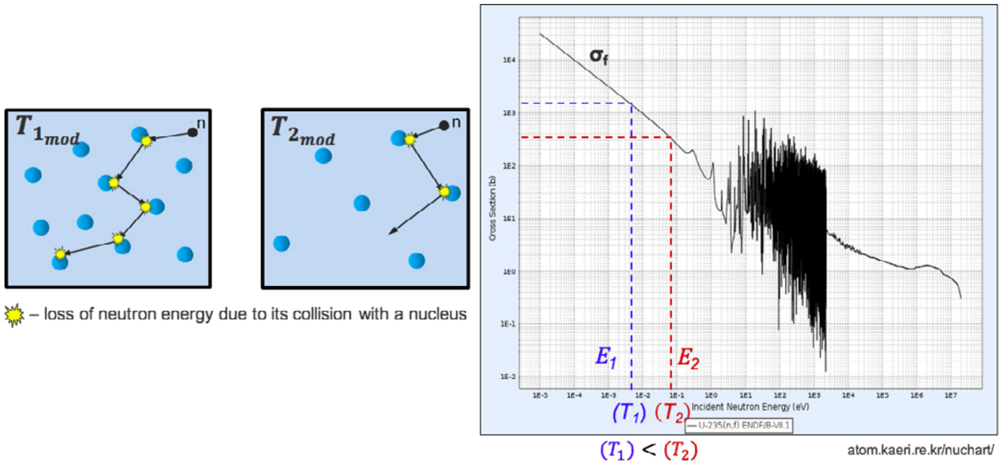

Figure 4.2.4. *MTC effect explained via cross-section.*

As seen in Figure 4.2.4, the higher the temperature, the higher velocity of neutrons in moderator. If a neutron increases its energy and velocity, fission cross-section is reduced. Moderator temperature increases→moderator density decreases→ moderator efficiency decreases→neutron energy increases→ the number of fissions drops. So, reactivity decreases and the reactor is again in a stable condition. Nuclear power reactor is rather different from nuclear weapon: it can shut down by itself if something uncontrolled happens inside.

Void coefficient (VC)

As mentioned before, an unexpected temperature increase presents the most danger during reactor operation. If, due to some effect, water from the reactor comes out of the reactor, the temperature of rest of the water in the reactor increases, and the water might boil. Boiling of the water leads to a drastic increase in pressure. This fact should be taken into account when choosing structure materials.

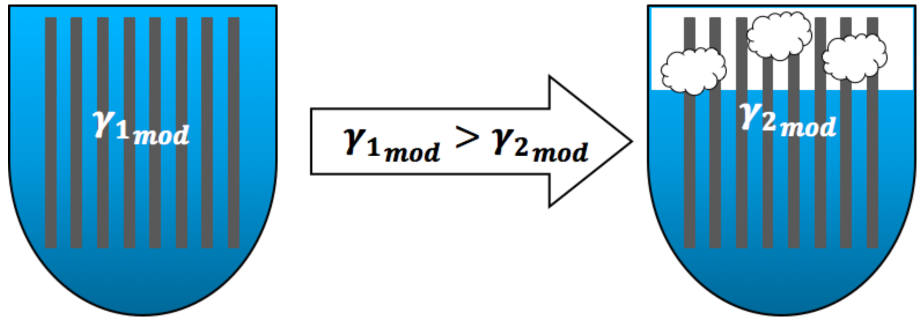

Figure 4.2.5. *Change of the void volume in the reactor.*

Reactor ***void coefficient*** (VC) in terms of reactivity is defined as the change of reactivity for two different densities per percent change in void volume:

$VC = (\rho(\gamma_2) - \rho(\gamma_1)) / \Delta V$, *where* γ denotes atom density, the number atoms per unit volume.

Importantly, when the void fraction is increased, the number of atoms per unit of volume of moderator is decreased, the moderation effect is reduced, and all phenomena mentioned above affecting the chain reaction propagation are in favor of reactor shutdown.

Values of reactivity coefficients (fresh fuel)

Typical values of the reactivity coefficients for fresh fuel (UO_2 fuel with 5% of uranium-238) in the Russian reactor VVER-1000 are shown below.

$\Delta T_{fuel} = 100°C$ ⇨ $DC = \dfrac{\rho(T_2) - \rho(T_1)}{\Delta T}$ ⇨ **-1.831 pcm**

$\Delta T_{moderator} = 20°C$ ⇨ $MTC = \dfrac{\rho(T_2) - \rho(T_1)}{\Delta T}$ ⇨ **-14.510 pcm**

$Voidage\ is\ 50\%$ ⇨ $VC = \dfrac{\rho(\gamma_2) - \rho(\gamma_1)}{\Delta V}$ ⇨ **-173.608 pcm/%**

The numbers are the same for the AES-2006 design. Doppler coefficient is negative, moderator temperature coefficient is negative, void coefficient is negative. All effects of reactivity are required to be not positive by the safety standards of the International Atomic Energy Agency. They are negative in the case of VVER, which is a good inherent safety parameter of VVER technology.

2.5. *Comparison of specific characteristics of VVER vs PWR*

In this section, the main differences between Russian (VVER) and western PWR technology are discussed. Table 2.5.1 presents general characteristics for a variety of reactors. At the bottom of the table, there is a comparison between PWR (western type) and VVER (Russian type).

Reactor type	Fuel material	Fuel rod cladding[1]	Typical assembly	Enrichment
AGR	UO_2	Stainless steel	Circular array of pins in graphite sleeve	2-4%
BWR	UO_2	Zircaloy-2	Square array	Up to 4.95%
Magnox	U metal	Magnox alloy	-	Natural
RBMK	UO_2	E110, E635	Circular array	Up to 2.8%
PHWR	UO_2	Zircaloy-4	Circular bundle	Natural
PWR	UO_2	Zircaloy-4	Square array	Up to 4.95%
VVER	UO_2	E110, E635	Hexagonal array	Up to 4.95%

Table 2.5.1. *General characteristics of various reactors. Source: Nuclear Technology Review published in 2007 by the International Atomic Energy Agency.*

1 *Zircaloy-2 and -4 are alloys of zirconium with about 1.5% tin as the main alloying element. Magnox alloy is magnesium with about 1% aluminium or zirconium. Both E110 and E635 are alloys of zirconium with about 1% niobium.*

The difference is mostly terminological—the physics is the same in both types. Uranium, structural materials, neutrons are the same and have no nationality. Fuel material is uranium dioxide in both reactors. Fuel rod cladding in western-type reactor is Zircaloy; in Russian type reactor, it is E110, E635. Another difference is in the typical assembly arrangement: a square array in the western-type reactor and a hexagonal array in the Russian-type. Enrichment is the same, up to 4.95%. So, the difference between two technologies is in the choice and selection of structural materials.

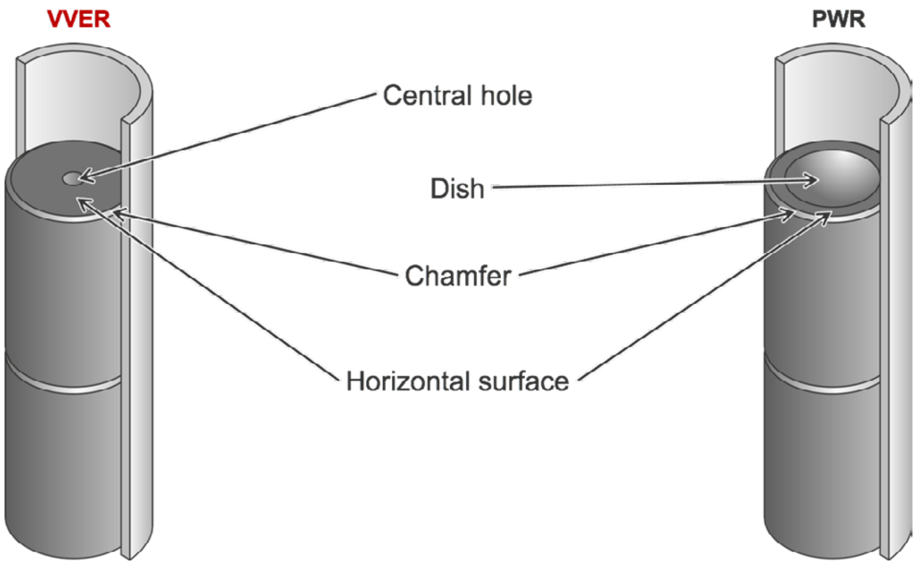

Figure 2.5.1. *Fuel pellets in VVER vs PWR.*

Figures 2.5.1 and 2.5.2 illustrate these differences. Figure 2.5.1 shows the specifics of fuel pellets: in Russian-type reactors, there is a central hole in the pellet, while in the western-type there is no hole. The reason for the hole in the design of Russian fuel pellets is as follows. When swelling of the fuel pellet occurs, the resulting pressure moves fuel material inside the pellet. So, fuel pellets play the role of stabilizer of the swelling from a certain point of view. There is another reason: since the temperature maximum is reached in the center of fuel pellets during the unfavorable transient condition of the reactor, the probability of fuel melting is lower for the Russian type of fuel than for the western type. Russian engineers were focused on safety from the very beginning of reactor technology development. As was mentioned in section 2.2, fuel burnup is the most important reactor characteristic from the viewpoint of economic efficiency. PWRs are preferable if only fuel burnup is considered: their level of burnup is higher. In Russian-type reactors, fuel burnup is lower because there is less fuel in fuel pellets. On the one hand, holes in fuel pellets reduce fuel mass and consequently, fuel burnup—but improve safety characteristics on the other hand. The balance of safety and economic efficiency should always be considered very carefully. Russian engineers give fuel safety larger weight in this case.

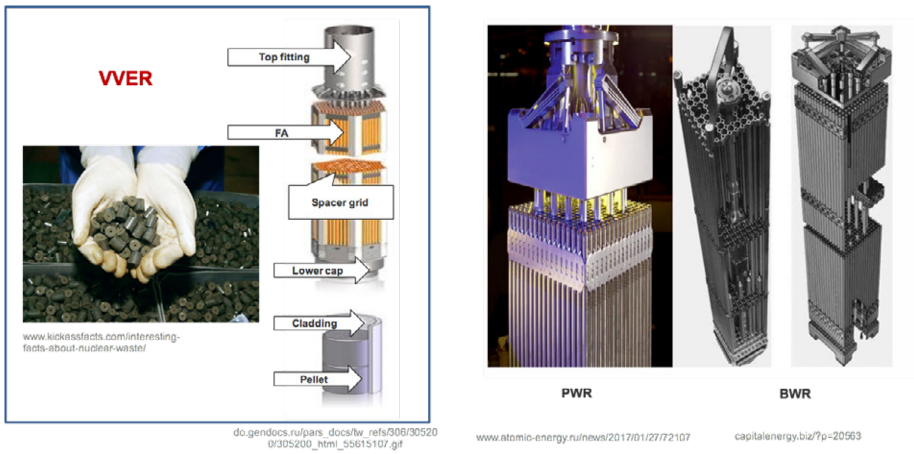

Figure 2.5.2. *Specifics of fuel assemblies.*

Figure 2.5.2 illustrates another difference between the reactors: the western-type square arrangement of the fuel element on the right side and the Russian-type hexagonal arrangement on the left side. Also pictured are VVER fuel pellets with a hole inside.

Specifics of VVER cladding

Zirconium is the main component in the fuel coating material for both PWR and VVER. This material has a very low neutron capture. The cladding is made from either Zircaloy for PWR or Russian types of alloys (E110, E635) for VVER. Figure 2.5.3 and Table 2.5.2 present the results of experimental investigation of these materials, published in an American journal in 2005, which demonstrate that zirconium-niobium alloy (Zr-1%Nb-O) in VVER is more resistant to oxidation than Zircaloy in PWR. After irradiation, spent fuel is taken from the reactor and put in some substance in order to cool it. Usually, the substance is water in a cooling pool near the reactor. Special care should be taken with the purity of the water. From the viewpoint of resistance to corrosion, Russian-type reactors are preferable. This technological feature of spent fuel management in Russian-type reactors is advantageous, especially for potential newcomer countries.

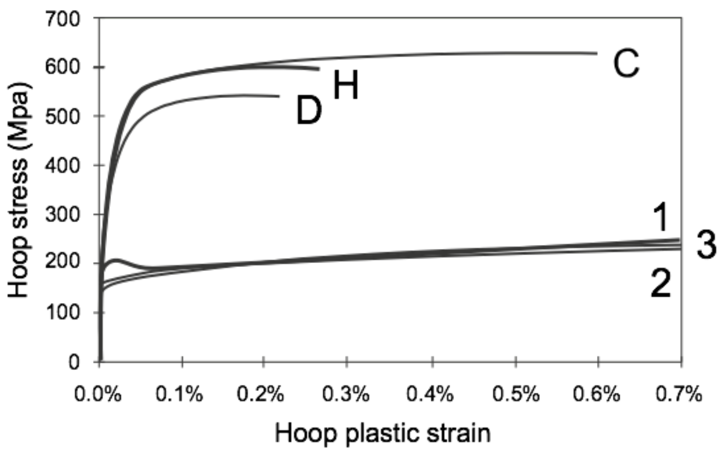

Figure 2.5.3. *Mechanical strain test results for different types of alloys. Denotation available in Table 2.5.2.*

Specimen	Material	Mechanical test	Test temperature
1	Zr-1%Nb-O	Internal pressure	350°C
2	Zy-4	Internal pressure	350°C
3	M5™	Internal pressure	350°C
C	Zr-1%Nb-O	Internal pressure	350°C
D	Zy-4	Internal pressure	350°C
H	M5™	Internal pressure (stress relaxation at E = 0.8%)	350°C

Table 2.5.2. *Mechanical strain test conditions for different types of alloys. Source: F. Onimus et al. Plastic deformation of irradiated Zirconium alloys: TEM Investigations and Micro-Mechanical Modelling, J. of ASTM International, Vol. 2, 2005.*

Extensive tests and over 20 years of experience proved the safe operation of cladding made of 1%Nb zirconium alloy E110 at temperatures below 350 °C. It has been detected that this val

ue is the lowest temperature for structural changes in material. Below 350 ºC there is no evidence of plastic deformation or any other mechanical phenomena. To improve plastic deformation resistance, the E635 alloy (1% Nb, 1.5% Sn, 0.5% Fe) was introduced in 2000.

Evolution of VVER fuel. Three major leaps

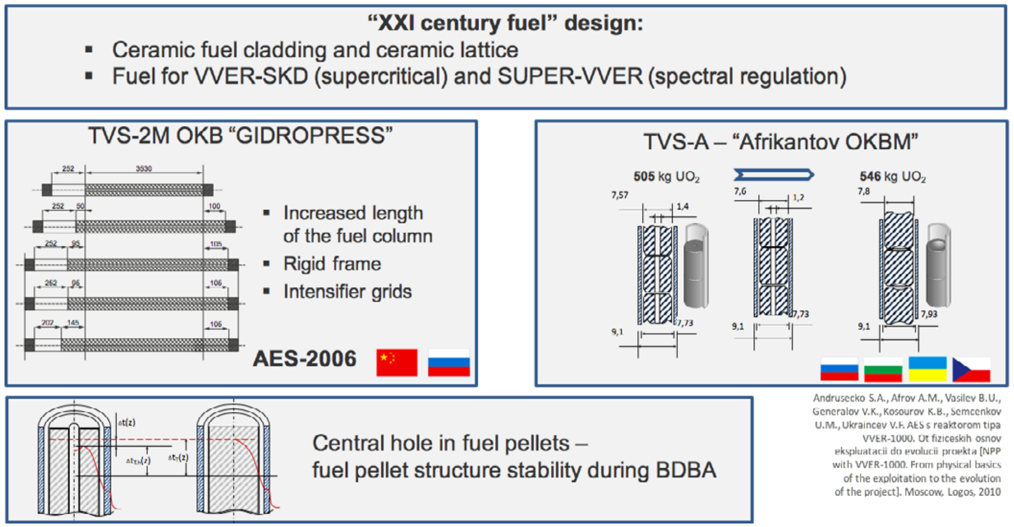

Figure 2.5.4. *Evolution of VVER fuel.*

Figure 2.5.4 shows the evolution of the Russian type of fuel used in VVER. There were three major steps in the development of the Russian fuel assemblies. TVS-A, which was recently introduced by Afrikantov OKBM company, has more fuel inside the fuel element, resulting in more fuel inside the fuel assembly and consequently, higher fuel burnup. So, step by step Russian technology, especially fuel fabrication technology, approaches the high values of fuel burnup.

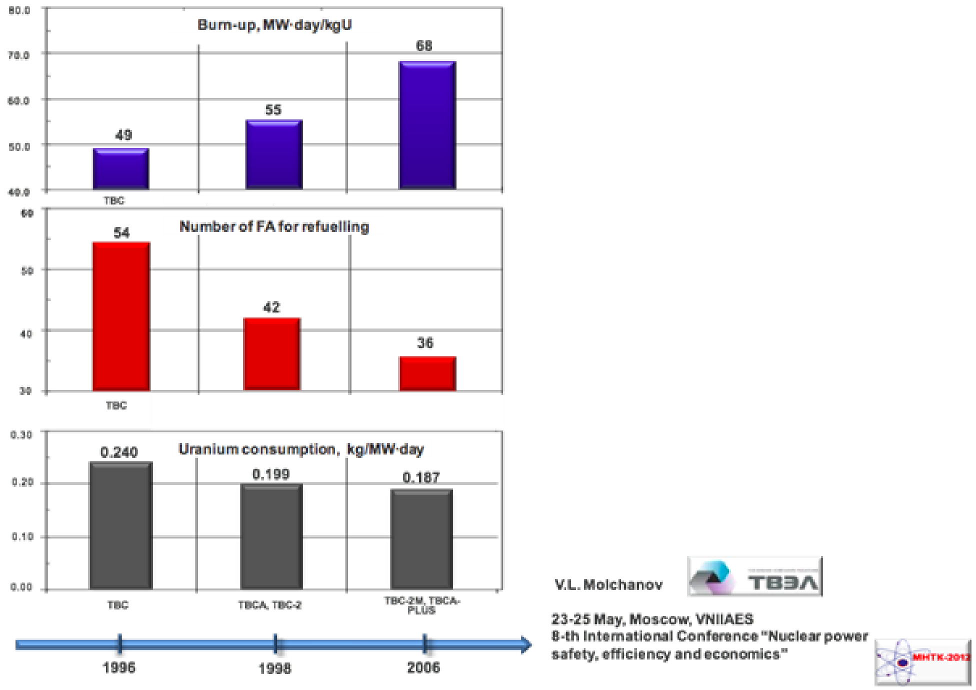

Figure 2.5.5. *Fuel assembly evolution.*

Figure 2.5.5 shows that recent levels of fuel burnup in VVER reach 68 MW-day per kg of fuel inside the element. That is a high value and Russian fuel manufacturers are proud of it.

Specifics of reactor vessel

Another interesting point in the comparison of Russian and western technology is the reactor vessel differences. Table 2.5.3 summarizes fuel vessel parameters of various designs: AP1000, VVER-1200 (AES-2006), APR-1400, EPR-1600.

Parameters	AP1000	VVER-1200	APR-1400	EPR-1600
Total height, inside, mm	12,056	11,185 (outside)	14,800	13,083
Inner diameter of cylindrical shell, mm	4,039	4,250	4,655	4,870
Wall thickness of cylindrical shell, mm	203	197.5	284	250
Design pressure, MPa	17.2	17.6	17.2	17.6
Design temperature, °C	343.3	350	343.3	351
Transport weight, t	340	330	573	520
Specific weight, t/MW	0.34	0.28	0.41	0.32

Table 2.5.3. *Main parameters of reactor vessels. Source: Markov S.I., JSC "RPA "CNIITMASH". Steel grades 15Kh2NMFA, 15Kh2NMFA, 15Kh2NMFA-A Class 1 for reactor VVER-TOI.*

As could be seen in Table 2.5.3, reactor vessels have different weights, masses, and heights. One of the most important characteristics, however, is the specific weight of the reactor, i.e. the mass of the material divided by the installed power capacity. The Russian design has the lowest, and best, value of this characteristic. It is an achievement of Russian material science which is actually a technological necessity. In western countries, nuclear power plants are usually constructed on the seashore, so reactor vessel is transported to the place of construction by sea. This type of transportation is not restricted by the reactor size. In Russia, NPPs are mostly built inland, because population density on the shore is not so high. Reactor vessel has to be transported by railroad, which imposes limitations on reactor size. This is the reason why Russian engineers concentrated on high quality materials and achieved best results in terms of material arrangement for reactor vessels.

Factors influencing reactor vessel design include: neutron fluence, mechanical and thermo-mechanical load, long-term exposure of the base material to high temperatures.

Figure 2.5.6. *Reactor pressure vessel shell of VVER. Base material: Steel 15H2NMFA mod.cl.1. Source: www.nuclear.ru/news/96219/.*

Specifics of design (vertical vs horizontal steam generator)

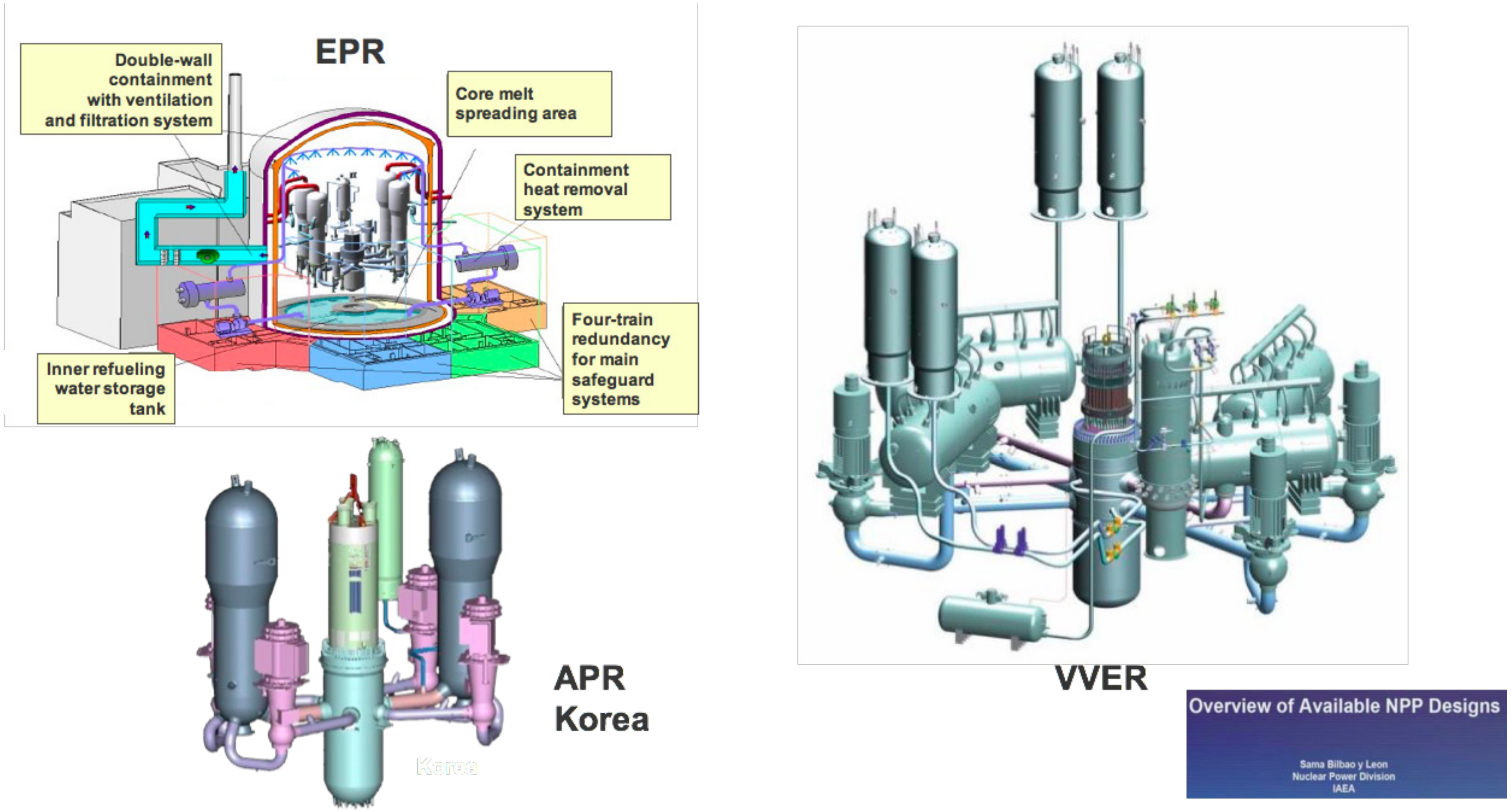

Figure 2.5.7. *Vertical vs horizontal steam generators.*

Another distinguishing point of VVER technology is the arrangement of steam generator. Figure 2.5.7 illustrates the layouts of EPR, APR, and VVER reactors. As seen in the diagrams, VVER steam generators have horizontal arrangement. In EPR and APR, the arrangement is vertical. From the viewpoint of neutronics and nuclear physics, it does not make any difference; technologically, the difference is huge.

NPP	Country	Supplier	Connection to Grid	Reactor Vessel Head Replacement	SG Replacement
BEZNAU-1, 2	Switzerland	WH	1969, 1971	2007, -	1993, 1999
R.E. GINNA	USA	WH	1969	2003	1996
MIHAMA-1, 2	Japan	WH	1970, 1972	2001, 2000	1996, 1994
POINT BEACH-1, 2	USA	WH	1970, 1972	2005, 2005	1983, 1996,
H.B. ROBINSON-2	USA	WH	1970	2005	1984
PALISADES	USA	CE	1971	Never	1990
NOVOVORONEZH-3, 4	Russia	Gidropress	1971, 1972	Never	Never
TURKEY POINT-3, 4	USA	WH	1972, 1973	2004, 2005	1981, 1982
SURRY-1, 2	USA	WH	1972, 1973	2003, 2003	1981, 1980
OCONEE-1, 2, 3	USA	B&W	1973, 1973, 1974	2003, 2004, 2003	2003, 2004, 2005
FORT CALHOUN-1	USA	CE	1973	2006	2006

Table 2.5.4. *Oldest NPPs with PWR (connection to the grid 1969 to 1975). The issue of steam generators. Source: www-pub.iaea.org/MTCD/Publications/PDF/Pub1337_web.pdf*

NPP	Country	Supplier	Connection to Grid	Reactor Vessel Head Replacement	SG Replacement
BORSSELE	Netherlands	S/KWU	1973	Never	Never
PRAIRIE ISLAND-1, 2	USA	WH	1973, 1974	2007, 2005	2004, 2013
KOLA-1, 2	Russia	Gidropress	1973, 1974	Never	Never
KEWAUNEE	USA	WH	1974	2004	2001
INDIAN POINT-2	USA	WH	1973	-	2000
THREE MILE ISLAND-1	USA	B&W	1974	2003	2009
TAKAHAMA-1	Japan	WH/MHI	1974	1996	1996
ARKANSAS ONE-1	USA	B&W	1974	2005	2005
DOEL-1	Belgium	ACECOWEN	1974	-	2009
BIBLIS-A (KWB A)	Germany	KWU	1974	Never	Never
RINGHALS-2	Sweden	WH	1974	1996	1989

Table 2.5.4. *Oldest NPPs with PWR (connection to the grid 1969 to 1975). The issue of steam generators. Source: www-pub.iaea.org/MTCD/Publications/PDF/Pub1337_web.pdf*

Table 2.5.4 presents statistical information about the oldest nuclear power plants with PWRs and VVERs installed, connected to the grid between 1969 and 1975. The majority of NPPs suffered from the very expensive operation of steam generator replacement. Steam generators are extremely vulnerable elements of NPPs. So, the majority of them were replaced—except for steam generators in the Novovoronezh and Kola NPPs (Russia) and ones in Germany and Netherlands. The results are qualitatively clear: Russian steam generators are preferable compared to PWRs in terms of replacement frequency.

Main distinguishing features

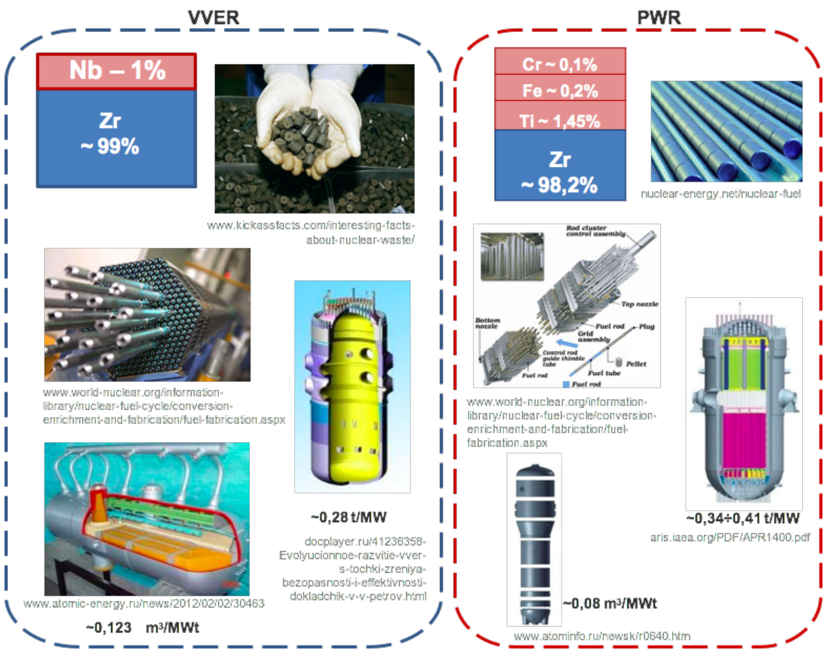

Figure 2.5.8. *Main distinguishing features of VVER vs PWR.*

The main distinguishing features between VVER and PWR technology are summarized in Figure 2.5.8. In particular:

1. Fuel element cladding (Zr-Nb alloy) is more resistant to oxidation in VVER technology.
2. Central holes in VVER fuel pellets make them more stable during beyond design-basis accidents (BDBA).
3. Hexagonal fuel assembly arrangement in VVER leads to uniformity of neutronics parameters.
4. Material for VVER reactor pressure vessel has low specific weight, which is preferable from the viewpoint of transportation.
5. Horizontal steam generators have larger coolant inventory, better natural circulation, and very good economic efficiency characteristics.

Remarkably, the first in the world core catcher—special equipment for controlling severe accidents—was installed in a Russian-type NPP built in China. The equipment for localization of corium (ELC) has been developed to ensure safety control in case of low-probable severe core melt accidents. The first NPPs to install this equipment were: Tianwan NPP in China and Kudankulam NPP in India, which is being constructed. Currently, many countries consider core catcher a critical element for ensuring safe performance of NPP. But the first one was installed in the Russian-type NPP.

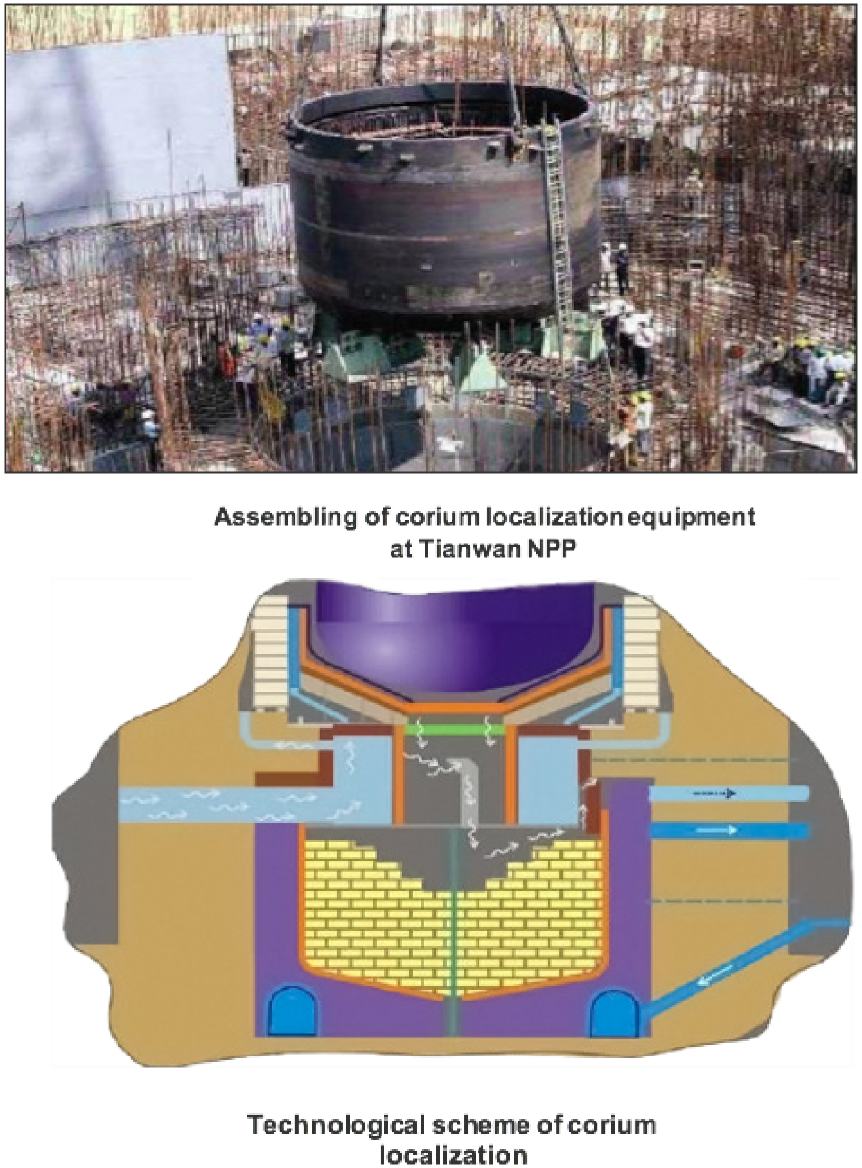

Figure 2.5.9. *A scheme of the corium localization equipment and its installation at Taiwan NPP.*

2.6. *Advanced nuclear fuel types for nuclear power reactors in Russia*

Fuel based on reprocessed materials

Section 2.5 covered the main differences between the Russian-type and western-type technology in terms of material arrangement. Section 2.6 concerns another distinguishing characteristic of the Russian approach to potential markets. A lot of attention is paid to developing new types of fuel by Russian physicists and engineers, which led to successful use of not only reprocessed uranium, but new REMIX fuel. Reprocessed uranium (RepU) is uranium extracted from spent nuclear fuel (SNF) during radiochemical processing, mixed with a portion of enriched uranium, and returned back to the fuel cycle to save the uranium resources. This technology is currently used in Russia: reprocessed uranium is taken from VVERs and used in RBMK-type reactors.

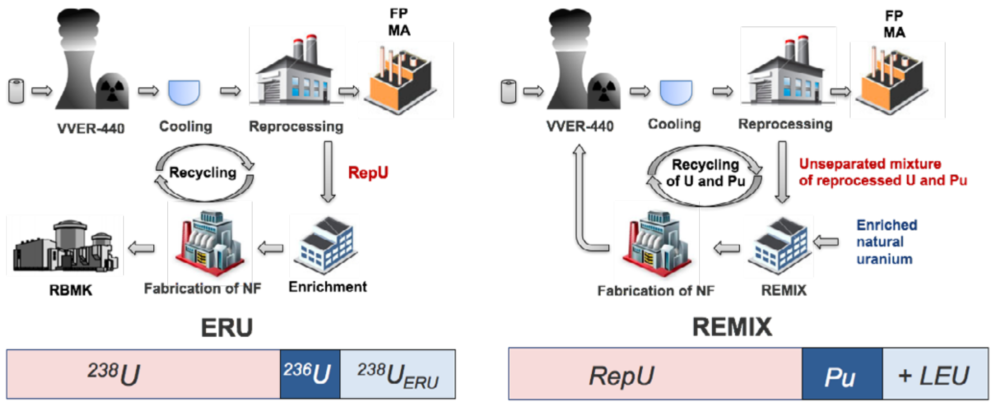

Figure 2.6.1. *Nuclear fuel cycles based on reprocessed materials: enriched reprocessed uranium (ERU) cycle vs REMIX cycle.*

REMIX fuel is a non-separated mixture of uranium and plutonium from LWR (light water reactors) SNF reprocessing, with addition of enriched uranium (natural or reprocessed).

Recently, Russian scientists succeeded in experimental use of so-called REMIX fuel, which is a regenerated mixture of uranium and plutonium accumulated in the reactor. REMIX fuel utilizes advantageous properties of plutonium-239, which is accumulated and fissioned in the reactor. Importantly, the portion of plutonium-238 in the new fuel is increased compared to conventional fuel. And plutonium-238 is very difficult to separate from plutonium-239. It is absolutely impossible to make a nuclear weapon from this kind of reactor-grade plutonium. Russia is considering entering new markets, especially in newcomer countries, with this type of advanced fuel.

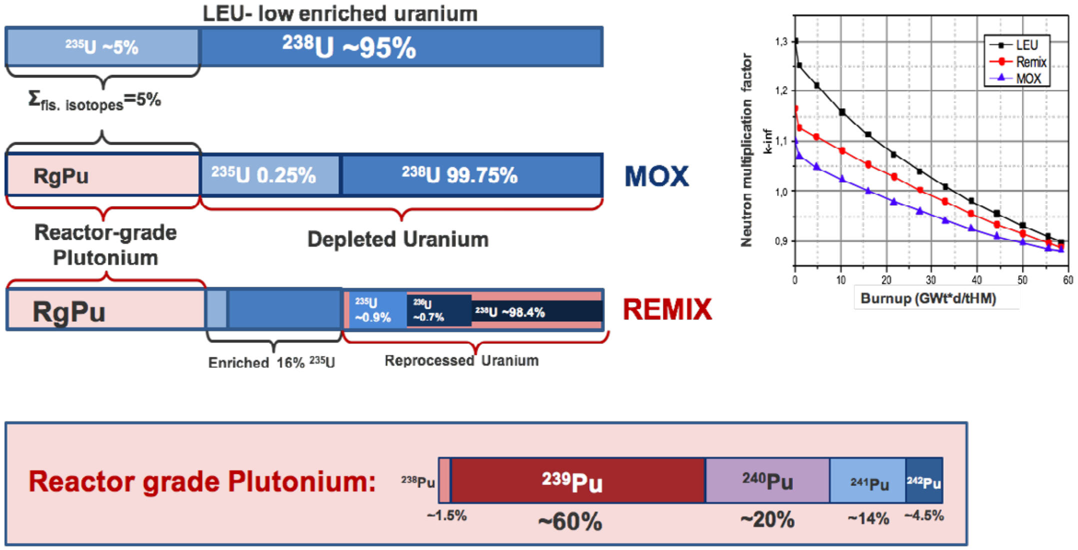

Figure 2.6.2. *Comparison of LEU, MOX, and REMIX nuclear fuels.*

Reactivity coefficients	Beginning of cycle			End of cycle		
	UOX	MOX	REMIX	UOX	MOX	REMIX
DC, pcm	-1.831	-2.520	-2.603	-1.042	-1.745	-1.300
MTC, pcm	-14.510	-22.76	-15.44	-2.154	-0.778	-1.898
VC, pcm/%	-173.608	-135.583	-234.537	-149.665	-82.889	-131.69

Table 2.6.1. *Reactivity coefficients of UOX, MOX, and REMIX fuels in VVER.*

Table 2.6.1 presents reactivity coefficients, which are very important for reactor safety performance. The Doppler coefficient (DC), moderator temperature coefficient (MTC), and void coefficient (VC) are calculated for three types of fuel: uranium dioxide conventional type (UOX), a mixture of plutonium oxide and uranium dioxide (MOX), and REMIX fuel. In the beginning and in the end of the irradiation cycle, all reactivity coefficients are negative. Therefore, reactor operation is considered to be safe.

History of implementation

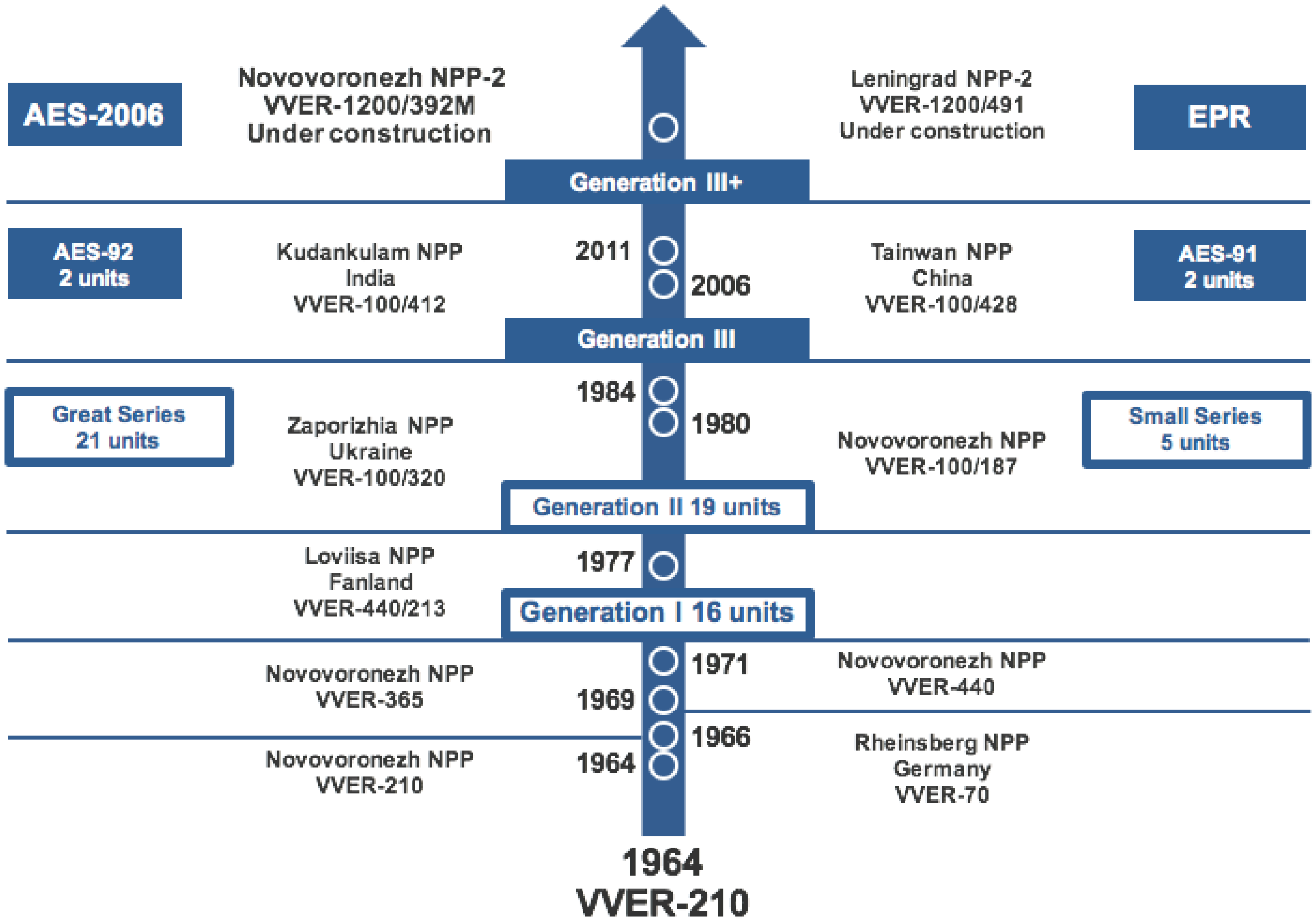

Figure 2.6.3 illustrates the evolution of VVER technology. It started in 1964 in Novovoronezh NPP in Russia. After Russia, eastern Germany was interested in using VVER—it was the second country to implement VVER technology. And step by step, we have reached the new AES-2006 design, which is considered to be reference technology for many international customers, including newcomer countries.